THE BALLARAT METEORITE, A FOSSIL IAB IRON FROM VICTORIA, AUSTRALIA

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The Ballarat meteorite was discovered in a palaeoplacer ('deep lead') deposit during gold mining in the Park Company leases at Ballarat, Victoria, during the late 1860s to early 1870s. The meteorite is a 12–15g fragment from a type IAB iron that underwent disaggregation due to weathering and transport in a vigorous stream environment. The meteorite consists essentially of kamacite with a subgrain texture marked by partially resorbed Neuman bands and with plentiful schreibersite inclusions. The average nickel content is in the range 6.1–6.3 wt. % as determined by EPMA and INAA methods and with high Ge and Ga contents for the type. The maximum age of the meteorite is unconstrained but it is at least 3 million years old, as this is the age of the basalt flows that buried the palaeoplacer deposit immediately west of Ballarat. Reconstruction of the prebasaltic landscape indicates that the meteorite fell close to the drainage divide at the time and has probably not travelled far. The specimen has been preserved due to the reducing conditions maintained in the deep lead environment.

Key words: Ballarat, fossil meteorite, palaeoplacer, Victoria, IAB iron

THE BALLARAT meteorite is a new nickel-poor IAB iron found during 19th Century mining operations at Ballarat, Victoria, Australia. A single fragment, likely to have been about 15 g originally, was discovered in a buried palaeoplacer deposit in the Park Company gold mine between 1867 and 1874. The circumstances of its discovery are not known, but it appears to have found its way into the mineral collection of Henry Rosales (1820–1916), a Spanish-born, German-trained mining engineer, who was engaged in contract work in the region at the time. Rosales donated his mineral collection to the University of Melbourne in the 1890s. Many of his samples have original hand-written labels but, unfortunately, that for the meteorite fragment is missing. While its provenance may therefore be questioned, the overall documentation of the Rosales collection and the historical connections between Ballarat, Rosales and documented discoveries in the Park Company mine suggest the meteorite is authentic. The historical mineral collections of the University were transferred to Museum Victoria in the late 1980s and the meteorite was rediscovered some years later. At an unknown time, a small portion of the sample has been removed for analysis, which detected nickel. Whether this was done by Rosales at the Ballarat School of Mines laboratory is not known, but the sample was registered in the University collection as 'meteoric (sic) iron'. Following further investigation by the present authors, the Ballarat meteorite was approved by the Nomenclature Committee of the Meteoritical Society. It is catalogued as specimen E15649 in Museum Victoria's meteorite collection.

The discovery site

Rich shallow alluvial gold deposits were discovered in the Ballarat region in central Victoria in 1851. From the mid-1850s, mining began to follow the deposits deeper beneath younger sediments in the eastern part of the field and basalt flows to the west (Baragwanath 1923; Canavan 1988). Two major deep lead systems, the Inkerman and Golden Point leads, are buried by up to four lava flows of the Newer Volcanics, in places over 100 m thick in total (Fig. 1). Various companies took out leases and sank shafts to exploit the alluvial deposits. The Park Company was formed in November 1867 and by using several former companies' shafts, opened up rich alluvial deposits in so-called "reef wash", at depths between about 250 and 320 feet (75–100 m). These were in an area between the Inkerman and Golden Point leads to the north and southeast, respectively, and about 30 metres above them (Baragwanath 1946). Until it closed in March 1874, the mine produced 95 000 ounces of gold.

Although the precise location within the Park Company mine is not known, the coordinates for the discovery site of the Ballarat meteorite would be close to 37· 34' 15" S; 143· 49' 55" E.

Several other metallic minerals were collected from the Park Company lead at about the same time. Rolled fragments of native copper and galena were recorded by Krausé (1882, 1896). Galena and pyrite specimens from the mine were exhibited in the Philadelphia Exhibition of 1875/6. While there is no specific mention of 'native iron' being found, it appears that some systematic collecting of unusual metallic minerals was undertaken while the mine was operating.

Features and composition of the meteorite

The surviving piece of the Ballarat meteorite is a rough flattened mass of about 10 g, with dimensions 20 x 15 x 5 mm (Fig. 2). A fragment of about 1.5 g was removed to prepare a polished section and one of about 0.25 g for instrumental neutron activation analysis (INAA). There is only a very thin rust coating on the bright metal, which shows no propensity to alter under ambient conditions. The hackly surface of the piece suggests it is a fragment broken from a larger crystalline mass of kamacite, probably during transport.

In polished section the texture shows subgrains of kamacite crossed by partly resorbed Neumann bands and with scattered roughly prismatic crystals of schreibersite ('rhabdite') up to about 0.05 mm long (Fig. 3). In detail these have ragged margins marked by an unknown precipitate (possibly carlsbergite or, less likely, roaldite) that appears to represent an incipient reaction halo with the enclosing kamacite (Fig. 4). These features closely resemble those of the rhabdites described from the Veevers IIAB iron by Bevan *et al.* (1995). Throughout the matrix kamacite and along the boundaries of Neumann bands are minute grains of another unknown phase. One outer portion of the fragment shows markedly deformed features, suggestive of a strong localised impact during transport. Rhabdite crystals have been bent along shear planes in the deformed section. The boundary between this deformed region and the main kamacite body is possibly a fragmented schreibersite grain (Fig. 5).

The meteorite was analysed for major elements (Fe, Ni, Co, P) using an electron microprobe and for Ni and minor elements by INAA. The average Ni content from 22 microprobe analyses is 6.1 wt % (range 5.6–6.6), slightly lower than the 6.3 wt % obtained by the INAA method (see Table 1). Ga, Ge and Ir contents of 95, 480 and 1.1 i g/g, respectively, indicate that Ballarat is a low Ni, high-Ga and high-Ge IAB iron, rather than a IIAB iron.

Analyses of seven schreibersite grains gave a formula of $Fe_{1.64}Ni_{1.36}P$.

GEOLOGICAL CONTROLS ON AGE AND PRESERVATION

The palaeoplacer in which the Ballarat meteorite was found forms part of an extensive Cainozoic fluvial system in the West Victorian Uplands, in which rivers flowed north and south from an E–W-trending divide (Canavan 1988). The oldest palaeoplacers are

	Fe wt%	Ni wt%	Co wt%	P wt%	Ga ?g/g	Ge ?g/g	Ir ?g/g
Microprobe	94.17	6.10	0.36	0.035			
INAA		6.3			95	480	1.1

Table 1: Chemical analyses of the Ballarat meteorite

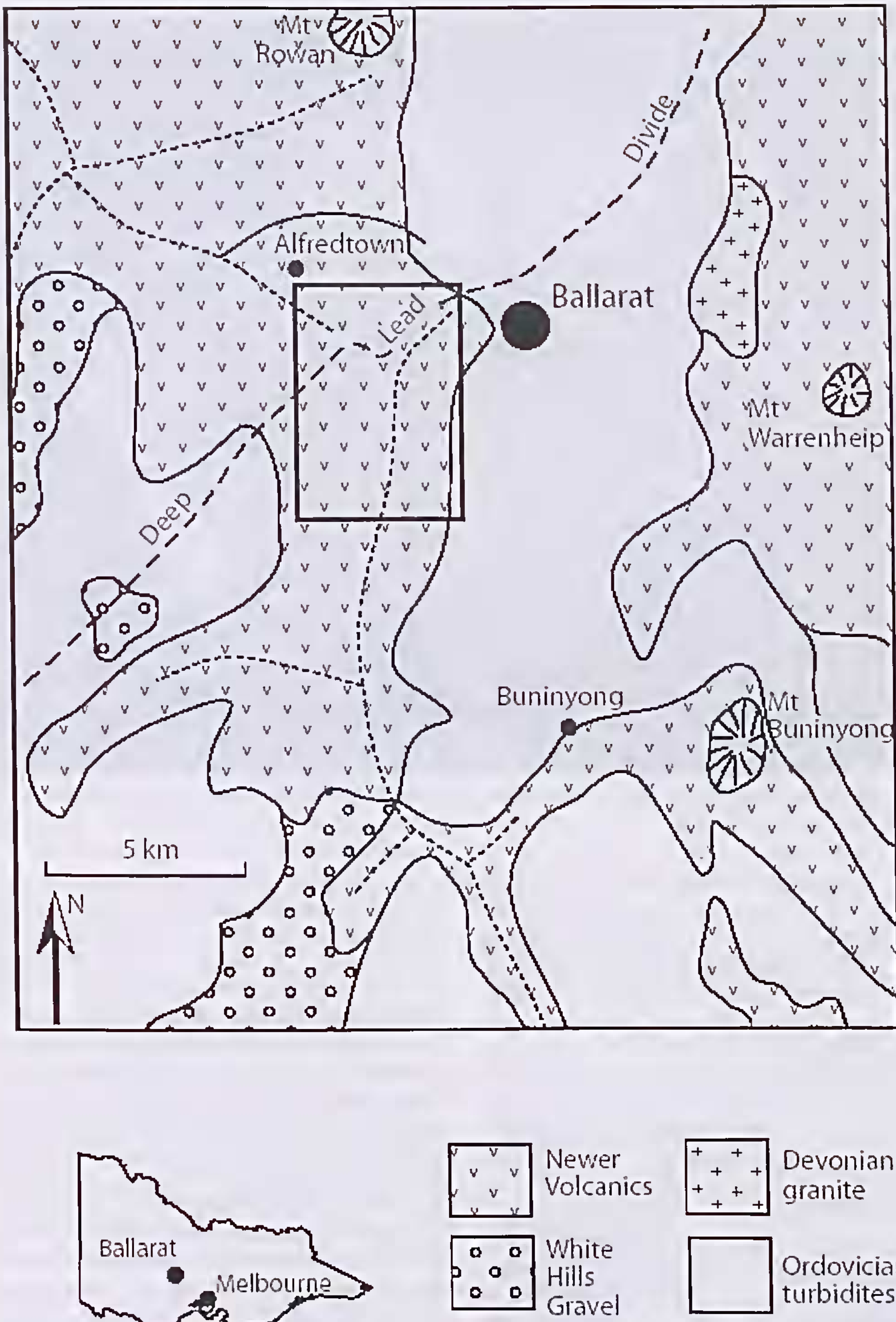

Fig. 1. Simplified geological map of the Ballarat district (after Finlay & Douglas, 1992). Main deep leads are shown as dotted lines. Lava flows from Mt Rowan eruption point cover the deep leads to the west of Ballarat, including the leases operated by the Park Company (see Fig. 6 for detail indicated by rectangle).

Fig. 2. The fragment of the Ballarat meteorite remaining after samples were removed for microscopy and analysis. The piece is 20 mm long. Museum Victoria specimen E15649.

unfossiliferous sheets of coarse quartz gravels known as the White Hills Gravel. These were laid down, probably in the very early Cainozoic, in broad shallow valleys cut into a landscape that had undergone extensive weathering. Later, younger, narrower valleys began to develop within the older broad valleys containing the White Hills Gravel. As this system advanced, streams eroded through the blanketing White Hills Gravel and incised valleys into the Palaeozoic bedrock, leaving remnant patches of gravel perched on interfluves. The conglomerates, sands, clays and lignites laid down in these new valleys were to become known as 'deep leads', which in many parts of the region were extremely rich in secondary gold. These palaeoplacers were deposited at different times and at different elevations, during cycles of down-cutting and back-filling. Many were subsequently buried by Pliocene and younger basaltic lava flows. Lack of fossils, later faulting and inadequate outcrop mean that the palaeoplacers are difficult to date and correlate. Dating of rare pollen remains shows that some of these deep leads began to develop as early as the late Eocene. However, deposition was long-lived and continued right through until the Pliocene, when extensive volcanism caused disruption of the palaeodrainage systems (Hughes & Carey 2002).

In the Ballarat goldfield, there are several types of gold-bearing palaeoplacers. Baragwanath (1923) considered that pre-basaltic 'deep lead reef wash', such as was worked in the Park Company leases in the western part of the field, was probably equivalent to remnant patches of gravel outcropping on low hills to the east. These exposed patches are now regarded as the early Cainozoic White Hills Gravel (Taylor et al. 1996). Historical descriptions of the buried reef wash describe a similar lithology of well-water-worn pebbles and boulders of quartz, some of enormous size, with subordinate fragments of bedrock (slate and sandstone) and pieces of water-worn siliceous cemented material from older deposits. Typically, reef wash

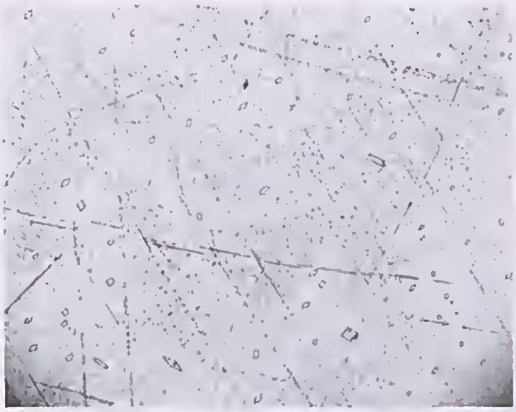

Fig. 3. General texture of the Ballarat meteorite showing subgrain boundaries in kamacite with partly resorbed Neumann bands and crystals of schreibersite. Field of view is about 1.5 mm across.

Fig. 4. Schreibersite prism showing incipient reaction halo with the enclosing kamacite. Field of view is about 0.08 mm across

deposits were spread over an expanse of flat or undulating bedrock above the normal level of the main stream channel or 'gutter' (Hunter, 1909). Channels up to 60 m deep were cut through the reef wash by later streams and filled with 'gutter wash' which, after burial by lava flows, form the deep leads proper.

The palaeodrainage system in the vicinity of the meteorite's discovery has been investigated by Taylor & Gentle (2002), using bore-hole data and mine records. A reconstruction of the prebasaltic bedrock topography suggests that a 'deep lead divide' separated the Inkerman and Golden Point leads. Trending generally NE–SW, the divide passed through the area mined by Park Company (Fig. 6). It appears that the reef wash the company removed came mainly from two poorly delineated remnants of an older fluvial system preserved on either side, but close to the top, of the divide.

This geological environment provides some constraints on the timing and location of the fall of the Ballarat meteorite. Based on the reconstruction of Taylor & Gentle (2002), the divide on which the meteorite-bearing gravels were perched immediately before the basaltic eruptions that buried them appears to have been close to the main continental divide when the White Hills Gravel was deposited in the early Cainozoic. This restricts the fall site of the meteorite to somewhere on or near this palaeodivide and therefore not far from its final resting-place in the Park Company leases. This is the case regardless of whether the 'reef wash' gravels in which the meteorite was found represent a patch of the White Hills Gravel preserved beneath the basalt, or a younger deposit associated with the early stages of deep lead formation. Such a distinction does, however, affect estimates of the maximum age of the fall. If the reef wash in the Park Company leases represents White Hills Gravel, then the meteorite could be as old or older than late Eocene, based on the time of deposition estimated for the White Hills Gravel by Hughes & Carey (2002). It could have fallen onto the Mesozoic surface that predates the White Hills Gravel before being incorporated into the deposits (Fig. 7). The minimum age of the fall is constrained by radiometric dates for basalts from the Ballarat region, which are between 2 and 4 Ma (Taylor et al. 1996; King 1985). The most representative age of 2.5–3 Ma is for lava from Mt Rowan, a volcano about 4 km to the northwest of the Park Company leases. This eruption point is the most likely

Fig. 5. Possible fragmented schreibersite grain along the interface between main body of fragment and deformed portion, marked by shear-bound etch markings. Field of view is 1.5 mm across.

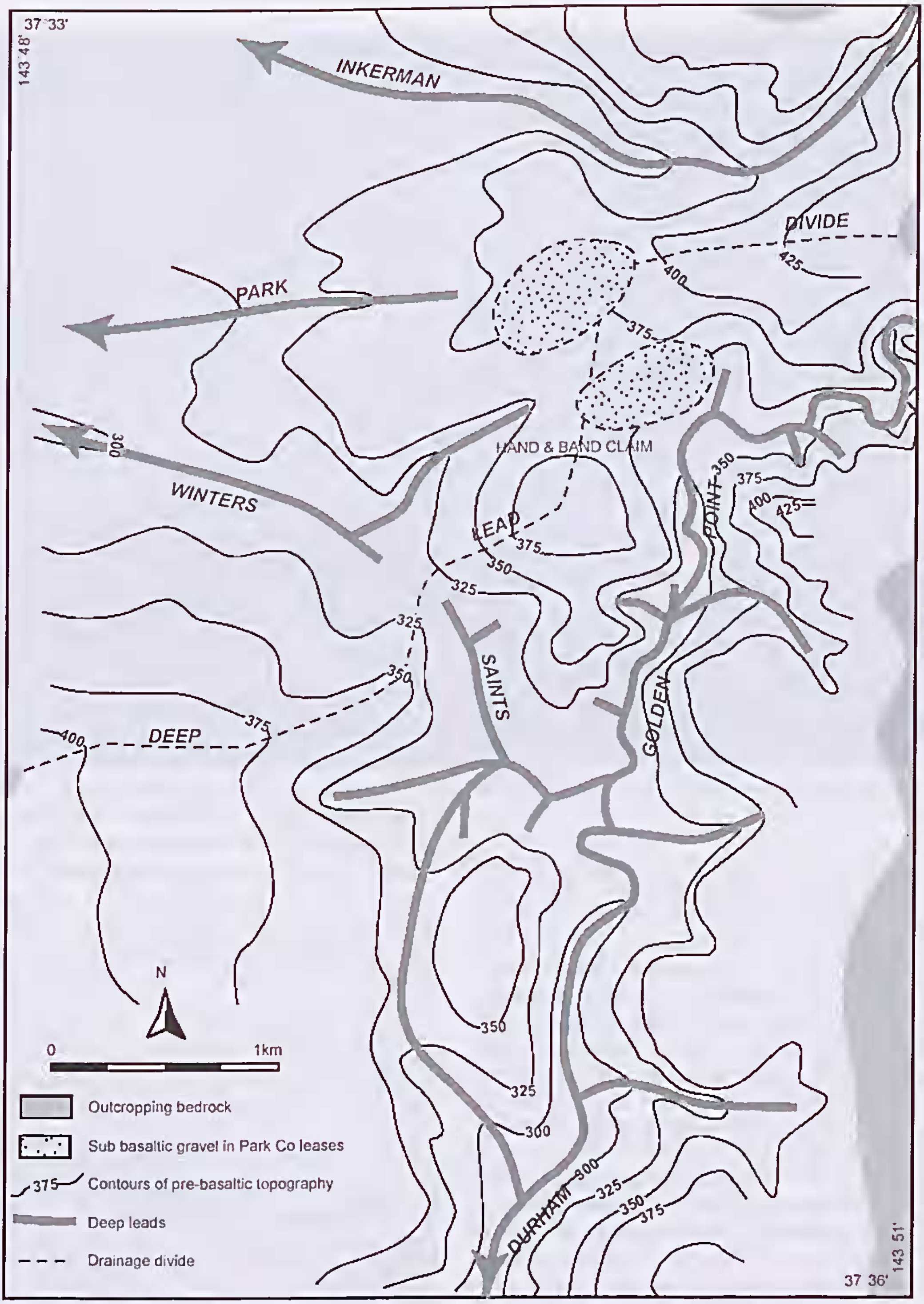

Fig. 6. Reconstruction of the prebasaltic topography in the vicinity of the Park Company leases, modified from Taylor & Gentle (2002). The positions of the areas of gravel wash mined by the Park Company are based on the geological map of Baragwanath (1923).

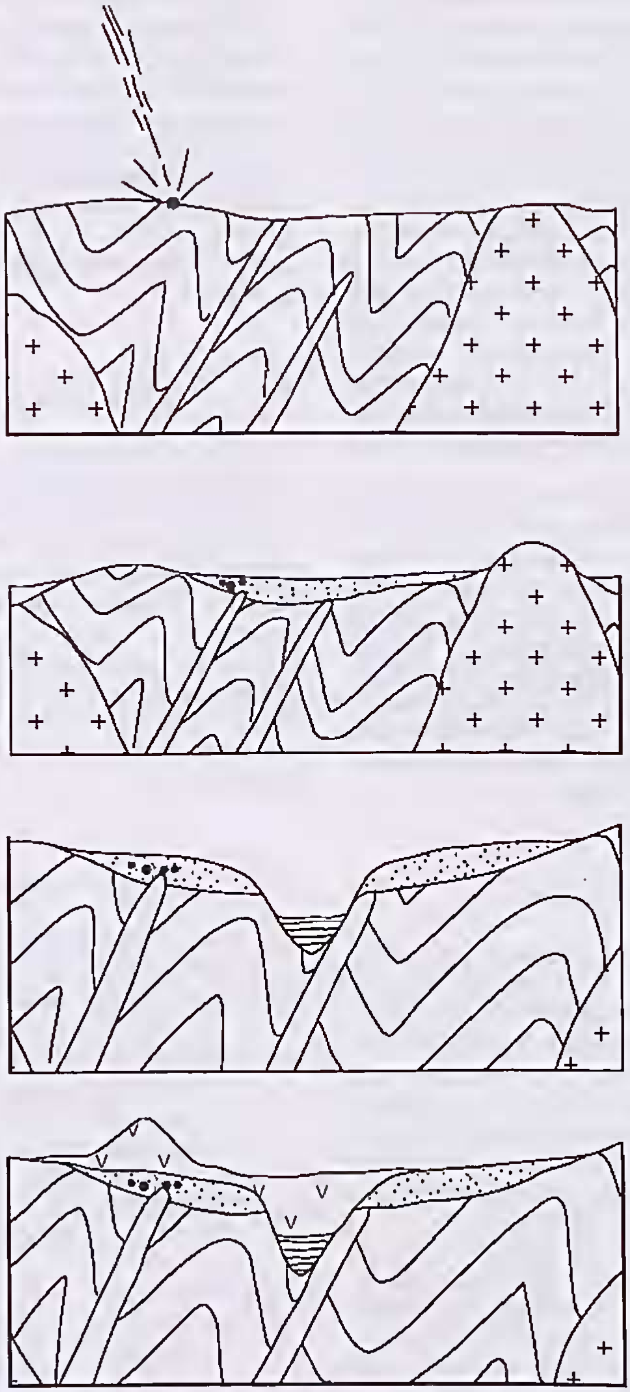

Fig. 7. Possible simplified history of the Ballarat meteorite in terms of the late Mesozoic – Cainozoic landscape evolution in the Ballarat district (after Taylor & Gentle, 2002). Having fallen on the weathered palaeosurface, possibly as early as the late Mesozoic, the meteorite was corroded and broken up during short-distance transport and burial. Subsequently, deep lead valleys were incised through the higher level alluvial deposits. Lava flows (3 Ma) buried these gravels and filled the deep leads.

source of many of the flows that buried the deep leads, including the uppermost flows at Alfredtown, less than 2 km west of the Park Company leases (Fig. 1).

The original size of the meteorite cannot be estimated, but it is likely that the surviving piece is from a much larger mass. At times, the fluvial deposits would have been high-energy environments, as indicated by the abundance of pebbles of massive reef quartz. Under these 'ball-mill' conditions, a relatively coarse-grained iron meteorite would tend to respond to impacts by fracturing along grain or subgrain boundaries, probably weakened by incipient oxidation, with adjacent regions being deformed. Schreibersite grains oriented along subgrain boundaries may have facilitated this fracturing (Fig. 5). Features of the Ballarat meteorite are consistent with such treatment and response.

Once buried by the lava flows, the placer deposits would have been immobilised and conditions would gradually have become reducing, particularly if organic matter was present. The widespread presence of pyrite layers in deep lead gravels indicates they were generally reducing environments. In this situation, a piece of meteoritic iron enclosed in the deposits was likely to survive. The reported presence of other metallic fragments, such as unoxidised copper metal and galena, in the Park Company lead is consistent with reducing conditions.

CONCLUSIONS

While the full circumstances surrounding the discovery and preservation of the Ballarat iron are unrecorded, there are sufficient links between the various strains of evidence to suggest it is a genuine occurrence of a fossil meteorite. It represents a kamacite plate or bundle of plates broken from a coarse-grained octahedrite. The microstructure of partially resorbed Neumann bands and incipient reaction haloes around rhabdite grains is evidence for mild annealing in a low-magnitude, short-lived heating episode.

Sometime before 3 Ma, the precursor mass of the Ballarat meteorite fell close to the main drainage divide in the Ballarat region. Following an unknown period of weathering, the meteorite was caught up in a high-energy fluvial environment that broke it into fragments. These were carried a short distance to be deposited in a placer deposit that was subsequently buried by 3-Ma basalt flows. At least one fragment survived in this environment to be collected during mining operations between 1867 and 1874.

The Ballarat meteorite (IAB) is one of the most common types of iron meteorite, with over 120 known examples. Yet its small size and the circumstances of discovery make it highly unusual. It is the smallest iron meteorite known from Victoria, supplanting Wedderburn (30 g) found about 125 km to the north of Ballarat in 1951. Possibly the only smaller iron meteorite known is Castray River, from Tasmania, with a total mass of about 10 g (Bevan, personal communication).

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